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AIRBORNE TACTICAL CONTROL SYSTEM PROPULSION STUDY-NOISE, VIBRATION, AND RADAR CHARACTERISTICS REPORT (U)

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PREPARED FOR:
Department of the Navy
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United Aircraft Research Laboratories

UNITED AIRCRAFT CORPORATION

EAST HARTFORD, CONNECTICUT

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Airborne Tactical Control System Propulsion Study - Noise, Vibration, and Radar Characteristics Report (U)

Prepared for the Naval Air Systems Command,
Department of the Navy, Washington, D. C. 20360

AIR 53602A

Contract N00019-68-C-0349

REPORTED BY J. E. Hesse
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APPROVED BY J. L. Cooley
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Airborne Tactical Control System Propulsion Study - Noise, Vibration, and Radar Characteristics Report (U)

SUMMARY

A brief research and analytical investigation was conducted under Contract N00019-68-C-0349, for the Naval Air Systems Command, AIR 53602, to determine the impact of powerplant radar, noise, and vibration characteristics on propulsion system selection and design for the airborne tactical control mission. Turboprop and turbofan noise, vibration, and radar cross section characteristics were compared on the basis of data available in the literature and data obtained by simplified analytic methods. Aircraft noise and vibration levels attributable to the powerplant were compared with criteria established for crew comfort for mission durations of the length required for the airborne tactical control mission. Radar cross sections for turboprop and turbofan powerplants were compared as to their influence on the relative detection range of the aircraft. The effects of propeller modulation of the reflected radar signal and the detection of this signal using moving-target-indication (MTI) radar were considered. It was found that the reduction of powerplant noise levels and radar cross sections warrant significant attention in the selection and design of the powerplant. The conventional turboprop installation presents a significant vibration problem because of blade passing in close proximity to the cabin. Propeller modulation of radar signals greatly increases the range at which the aircraft can be detected. It was concluded that unconventional turboprop designs warrant serious consideration; in particular, a shrouded turboprop may present an attractive alternative.

CONCLUSIONS

Noise

1. Noise is a rather severe problem for this mission. The long durations contemplated for the mission warrant cabin noise levels considerably below the levels that are achieved in the current E-2A design.

2. Low engine noise levels should be an important design criterion for the selection of a powerplant for this mission. Because of the low-frequency noise problem associated with a conventional turboprop, leading to a desire to reduce both tip speed and propeller diameter, consideration of an unconventional design

(such as a shrouded propeller) may be warranted. For the turbofan engine, special noise-reduction features should be considered.

Vibration

1. The only major design consideration affected by vibration for the airborne tactical control aircraft engines is the avoidance of high vibration levels at propeller blade passing frequencies.

2. Avoidance of undesirable cabin vibration at propeller blade passing frequencies will be difficult due to the direct-coupled nature of this vibration and the desirability of having the engines close to the cabin in case of an engine failure and to accommodate space-limited aircraft carriers. The desirability of reducing the effects of blade passing indicates that a shrouded propeller should be considered.

3. A conventional, under-wing, turbofan design will probably not present any significant vibration problems.

Radar

1. The design of the airborne tactical control aircraft powerplant should be strongly influenced by consideration of reducing radar reflectivity.

2. Since the conventional turboprop design presents a very poor design in terms of radar detection about a large azimuth angle relative to a turbofan, consideration should be given to a shrouded propeller.

INTRODUCTION

The current aircraft, the E-2A Hawkeye, used by the Navy for Airborne Tactical Control, is subject to potential problems in the areas of noise, vibration, and radar characteristics due to the nature of the mission. Noise and vibration can contribute to crew fatigue and low morale because of the requirement for long-duration missions and performance of exacting tasks in close quarters. The requirement to minimize the propulsion contribution to radar cross section and avoid interference with the radar operation of the E-2 is inherent in the airborne tactical control mission.

In order to determine the degree of severity of the noise, vibration, and radar problems associated with the powerplant, and in order to provide a preliminary basis for judging the impact of these problems on powerplant design and selection, a brief study was required in each problem area. A comparison of typical turboprop and turbofan installations was to be prepared, and general possibilities for alleviating problem areas were to be identified. Since the level of effort to be applied to the noise, vibration, and radar study was small, use was to be made of existing data where applicable and comparisons were to be kept at a general level.

The relevant data obtained in the study are described in the following three sections, NOISE, VIBRATION, and RADAR. The implications of these data are described in a final section, DISCUSSION OF RESULTS.

NOISE

Sound intensity is measured on the decibel and phon scales. A decibel rating defines a certain sound pressure level relative to 0.0002 microbar, while a phon rating defines a given loudness as perceived by the human ear. The two scale values are equal at a frequency of 1000 cps. The relationship at other frequencies is shown on Fig. 1 (from Ref. 1).

In judging the noise criteria that should be applied to the design of an airborne tactical control aircraft, it was assumed that crew comfort (as opposed to auditory effects) should dictate the acceptable levels. From a survey of data gathered on human reaction to noise such as is listed in Refs. 2 - 4, the tolerance levels indicated on Fig. 2 were judged to be representative of goals to be sought for cabin noise levels. Thus, for flight times of from 5 to 10 hours, 75 to 80 phons should be acceptable. (About 65 phons is considered very good for general commercial passenger operations.)

Current Noise Problem

Data obtained from Ref. 5 on the cabin acoustical noise environment of the current E-2A aircraft are indicated on Fig. 3. These data were taken at normal cruise power, 30,000 ft altitude. The 70 and 80 phon levels are shown on Fig. 3 to permit a comparison of the measured levels with the general levels considered acceptable. The measured levels significantly exceed the acceptable levels at all frequencies between the extreme ends of the octave band to which the human ear is sensitive.

Turboprop Engine Noise Measurements

Measurements made by Grumman (Ref. 5) of the noise generated by the E-2A during ground operation are shown in Table I. The coordinate system indicated for recording the measurements on Table I is useful for both measuring and predicting engine noise levels, since the engine is operated at a well-defined condition (military power), since the aircraft is stationary and therefore aerodynamic noise is not a factor, and since the measurements are made outside the aircraft cabin, eliminating the noise attenuation through the cabin walls. For these reasons, the conditions indicated on Table I are useful as a basis for comparing turbofan and turboprop noise levels. However, it is obvious that the noise levels indicated on Table I far exceed the levels measured in the cabin during normal cruise conditions. This comparison is made explicitly in Fig. 4, indicating a reduction of 20-30 db across the octave band. A comparison of cabin noise measurements given in Ref. 5 indicates reductions of 2-15 db between engine operation at military power, ground runs prior to takeoff, and operation at normal cruise power at 30,000 ft. Thus it can be inferred that a large portion of the reduction shown in Fig. 4 is due to attenuation trhough the cabin walls, although the amount of this reduction is sensitive to both the noise drequency and the position in the cabin. Information obtained in discussions with airframe manufacturers indicates that cabin wall attenuation of about 20 db is possible for frequencies above the 4th octave. For lower frequencies cabin wall attenuation is much less effective.

Turbofan Noise Predictions

A broad range of design parameters is being considered for all engine cycles being studies under this contract. In order to readily assess the potential noise problem to be encountered with turbofan engines, noise predictions were made by the Pratt & Whitney Aircraft Division of United Aircraft for a typical study turbofan. This typical turbofan is characterized by a bypass ratio of 7, a turbine inlet temperature of 2700 deg F, and an overall pressure ratio of 20. This study turbofan does not include any special noise-reduction features, such as are included in the "quiet" JT8D developed by P&WA for commercial service. The predictions were made for conditions consistent with the measured data for the turboprop engine given in Table I. The results of the predictions and the comparison with the turboprop data are shown in Figs. 5 - 7 for the three radials, 60 degrees, 90 degrees, and 120 degrees, as defined in Table I.

The comparison made in Figs. 5 - 7 generally indicates a noise advantage to the turbofan in the lower ocrave bands. This advantage may be particularly significant since the aircraft boundary layer noise may dominate the noise spectrum above the fourth octave band. Data taken from Ref. 1 indicates a boundary layer noise level of 123-db at the surface of an aircraft flying at 200 kts. This noise is heavily concentrated above the fourth octave.

VIBRATION

Human Tolerance

A broad and in-depth survey of the literature (c.f. Refs. 6-11) which contains data on human response to vibration has indicated some degree of consensus on what constitutes comfortable riding qualities in terms of vibration. Recommended tolerance limits at low frequencies are indicated on Fig. 8, as a function of fatigue time. For the mission times considered for the airborne tactical control mission, between 5 and 10 hours, between 0.06 and 0.03 g would be acceptable levels.

The vibration levels required to induce a given level of sensation in the body change markedly with frequency, being a minimum (i.e., the body being most sensitive) at frequencies between 2 and 20 (and particularly around 6) cycles per second. This is explained in Ref. 10 as being caused by the resonance of large segments of the body mass (such as the shoulders or visceral organs) which is overcome by tightening the appropriate body muscles, bringing on fatigue. At and beyond the upper end of this range, between 20 and 30 cps, the head resonates, particularly on the sitting crew member, with consequent deterioration of visual acuity.

The variation of comfort limits with frequency is shown in Fig. 9, expressed in terms of displacement and acceleration. (The displacement level was derived from the acceleration level by twice integrating a sinusoidal wave.) Although comfort criteria are often given in terms of acceleration, it is convenient for this study to display these criteria in terms of displacement since powerplant vibration levels are usually specified in mils (1 mil = 0.001 in.) measured across peak-to-peak (double-amplitude) displacements.

Propulsion Vibration Sources

The chief sources of powerplant-induced vibration are depicted on Fig. 10. The major components of vibratory motion produced by turbine powerplants occur at the rotational frequencies of the compressor(s). In addition, turboprops produce vibration at the propeller shaft rotational frequency and induce forced vibration of the wing and/or fuselage at the propeller blade passing frequency. Some of the vibratory motion produced by the powerplant will be transmitted through the wing strucutre to the cabin. Most nonresonant structures will transmit low-frequency vibrations better than high-frequency vibrations.

Compressor Rotational Frequencies

An example of a current turbofan engine is the JT8D. In this engine, the low compressor shaft turns at about 7,000 rpm, or 116 cps, and the high compressor shaft turns at about 11,000 rpm, or 183 cps. In general, the compressor shaft frequencies of turbofan engines will be between 100 and 300 cps. The vibration amplitudes at these frequencies are usually limited to four mils peak-to-peak displacement when measured at inlet, diffuser, and turbine case.

Turboprops, such as the T56, have similar compressor shaft speeds and produce similar vibration amplitudes at these frequencies.

Propeller Shaft Frequencies

Propeller shaft frequencies usually fall in the range of 10 to 30 cps. The vibration amplitude at the propeller shaft frequency can be on the order of 40 mils peak-to-peak displacement. This low-frequency vibration is difficult to isolate from the cabin structure because the structure tends to transmit low-frequency vibration unattenuated, and because resilient isolators tend to be very flexible when designed to operate at low (10 cps) frequency. The isolator stiffness will decrease as the square of the lowest isolation frequency.

Propeller Blade Passing Frequencies

The propeller blade passing frequency will be three or four times the propeller shaft frequency depending on the number of blades used. The vibration from this source is transmitted directly from the prop blade wakes to the adjacent wing and/or fuselage and is not necessarily transmitted through the engine mount structure. Therefore, resilient mounts used between the powerplant and the wing are short circuited and are uneffective. Direct coupling between the propeller and the wing or fuselage means that the structure will be less effective in attenuating vibration from this source and explains why turboprop aircraft often experience vibration of the cabin at the propeller passing frequency.

Experimental Turboprop Data

Experimental data from the Grumman E-2A aircraft incorporating T56 turboprop engines is offered to substantiate these positions (Ref. 5). The propeller shaft frequency of the T56 was 18 cps, and the propeller blade passing rate was 72 cps. As shown in Table II, significant vibration of the cabin and cockpit occurred at 12 cps, 18 cps, 25 cps, and 72 cps. Of these, the 18 cps and 72 cps components were attributed to the powerplant. The source of vibration at 12 and 25 cps was not identified. No vibration at frequencies above 72 cps was reported and presumably was not detected. Therefore it can be assumed that vibration associated with the compressor(s) was not transmitted to the cabin.

A comparison of some of the vibration test data for the E-2A with the comfort levels discussed previously is indicated on Fig. 11. If the comfort levels established are accepted as valid, then the vibration induced at the propeller shaft frequency is unacceptable during full power operation but acceptable during the important loiter condition. However, the vibration induced at the blade passing frequency is generally unacceptable.

Vibration Characteristics of Turbofans

The spectral distribution of vibration signals measured at turbine engine mount locations is broadband; however, the most significant components are the rotational frequencies of the engine rotors. Data from an FT4 engine is presented on Fig. 12 to illustrate this point. Aircraft with loosely coupled engines such as the Boeing 707 have not experienced any significant engine-induced vibration of the cabin strucutre other than the airborne noise radiated from the jet exhaust. The absence of structureborne noise is thought to be the result of attenuation of vibration by the flexible pylon and long flexible wing structure which constitute the link between the powerplant and the cabin.

Aircraft with engines installed on the aft fuselage, such as the Boeing 727, have demonstrated noticeable vibration in the cabin area between the engines. The vibration appears to be localized to the cabin area between the engines and does not propagate to the mid or forward sections.

Mount Strucutre

If the engine location is such as to present a high probability of the transmission of engine vibration to the cabin area, then consideration for employing damping treatment to the connecting structure would be reasonable. Riveted structures are better dampers than comparable welded structures. Box frames are better than solid structure. Numerous possibilities exist for designing the structure for minimum transmission of vibration. The airframe manufacturer is probably the best qualified to undertake this design and could be so directed.

Equipment Vibration Tolerances

The standards for military equipment, as given, for example, in the specifications listed in Ref. 12, indicate tolerance levels far in excess of the levels indicated for human comfort. It is felt that if the aircraft and engines are designed properly for human comfort, equipment problems induced by vibration will be so localized as to be readily alleviated by local isolation or damping techniques.

RADAR CHARACTERISTICS

Radar Range Equation

In terms of radar and target parameters, the maximum range at which a target can be detected with no prior knowledge of a target presence is given by the following equation:

$$R_{MAX} = \left[\frac{P_t \; G \; A_e \; \sigma \; L_T}{(4 \pi)^2 \; k \; T_o \; B_n \; F_n \; (S_o/N_o)} \right]^{\frac{1}{4}} \qquad (1)$$

where: P_t = Transmitted Power

G = Antenna Gain

A_e = Effective Aperture

σ = Radar Cross Section of Target

k = Boltzmann's Constant

T_o = Ambient Temperature

B_n = Noise Bandwidth

F_n = Noise Figure

S_o/N_o = Signal-to-Noise Ratio

L_T = Total System Losses

Examination of Eq. 1 indicates that the maximum range at which a target can be detected is proportional to the fourth root of the radar cross section of the target and is inversely proportional to the fourth root of the noise bandwidth of the system. The following sections consider the backscatter cross section of turboprop and turbofan engines and their relative cross sections. In addition, because the radar from the aircraft will be in competition with backscatter from clutter, e.g., waves on the ocean, some distinctive signatures which will permit the target to be identified in clutter are explored and their effects on target detectability considered. Future studies should explore techniques such as frequency agility, polarization, and signal integration.

Radar Cross Section of Engines

A turbofan engine of the size contemplated for this mission has been estimated to have a backscatter radar cross section (RCS) of 300 ft^2, whereas the backscatter cross section of a turboprop is estimated to have a cross section of 2000 ft^2. This RCS includes the backscatter from the propellers and fan blades.

Engine cavities return most of the echo because they act as retroreflectors returning the incident electromagnetic radiation with high directivity toward the radar. They do this over a relatively broad azimuth and elevation angular range around the nose-on and tail-on aspects in contrast with the specularly reflected waves from the rest of the aircraft. While the latter components of the echo can be large (particularly in the broadside aspect), they are large only in a very limited angular range, large surfaces forming narrow lobes at a given wavelength. Thus, susceptibility to detection is due more to echoes from the engines than from the rest of the aircraft.

Engine cavities act as retroreflectors due to their geometry of multiple internal reflecting surfaces guiding the incident wave around concave corners, ultimately redirecting large parts of it toward its source. It has been established (Ref. 13) that at the frequencies up to and including X bands the methods of geometrical optics are sufficiently accurate to estimate the angular spread of the return from cavities of the size of jet engines around the retro directions and thus to estimate the RCS. In particular, ray tracing methods are sufficiently accurate to determine those duct areas where the placement of RF-absorbing material will be most effective in reducing the echo.

Reducing the Reflectivity of Engines

The RF absorbers considered for locations determined by ray tracing inside the engine inlet and exhaust cavities are ferrite sheets in 3-4 millimeter thicknesses and of about 0.5 pounds per square foot per millimeter weight. They attenuate the S-, C-, and X- band RF power incident upon them by 10-15 db. At lower frequencies this performance of dielectric coatings is degraded.

Instead of using RF-absorbing covering materials, or in addition to their use, the engine intake may be covered by a cone-shaped screen in order to scatter the incident wave over a wide angle before it would reach the retroreflecting intake duct. Such measures applied without absorbers may produce a 10-12 db echo reduction in the nose-on aspect.

The exahust nozzle of the engine is the main source of echo in the tail region. Because the velocity of the exhaust gases is so high, the shaped screen used in the nose region can not be used over the exhaust. A possible satisfactory solution from both an electromagnetic and aerodynamic standpoint is to mount, if practical, a shaped plug in the nozzle in such a way that there is no direct line of sight to the rear of the engine. The RF echo reduction achievable is about 10 db. This factor can be increased by covering the portion of the plug facing the rear of the engine with RF-absorbing materials. The aerodynamic effects are small, of the order of one percent of engine thrust. It should be mentioned that the use of a porous plug can also reduce infrared radiation at the same time.

In some locations the ferrite absorber sheets have to be covered for aerodynamic reasons with a dielectric material. This will have little effect on the electromagnetic absorption qualities.

In summary therefore, it is felt that through the use of RF-absorbing material, the radar cross section of an engine may be reduced by 10 db from its uncamouflaged state.

Propeller Modulation

A significant factor in comparing propulsion systems is the effect of propellers on aircraft detectability. In coherent types of radar systems the echo from a moving traget will show a periodic fluctuation because of the target's radial velocity relative to the radar. With noncoherent systems this Doppler beat, so-called, is absent, but echoes from moving airplanes still show large fluctuations.

The most striking characteristic of propeller aircraft echoes is an almost periodic variation of the signal strength. It has been shown conclusively that this variation arises from a periodic modulation of the airplane's radar cross section as the propellers rotate. The nature and properties of "propeller modulation" have been studied intensively and are reported in detail in Refs. 14 and 15.

Figure 13 shows the signal from a B-26 bomber on a 10-cm system for an interval of about 0.1 sec. The periodicity is strikingly evident. The fundamental is given, not by the shaft speed itself, but by the shaft speed times the number of blades per propeller and is about 50 to 60 cps. It is obvious from the figure that the signal will contain significant harmonics of this fundamental frequency. Figure 14 shows the frequency spectrum of the signal in Fig. 13. The peaks indicate the intensity of the individual harmonics in terms of percent modulation. It is to be noted that the harmonic at three times the fundamental frequency is stronger than the fundamental. There is an appreciable contribution from as high as the tenth harmonic.

As is to be expected, the propeller modulation percentage is a function of the airplane's aspect. It is naturally greatest head-on, slightly less for the tail aspect, and considerably less broadside, where the reflection from the fuselage predominates. Figure 15, which is a record by Ashby and Martin (Ref. 14) of the propeller modulation of the signal from a B-26 as a function of aspect, illustrates these differences. The plot also shows that the pattern has a very detailed lobe structure. The same general dependence of propeller modulation on aspect is reported by Beeching and Corcoran (Ref. 14) who also state that (for the airplanes tested at the time) the greatest modulation, head-on, was found for a Mosquito airplane (65%) and the least for a B-17 bomber (25%).

If the propeller modulation signal is eliminated by averaging the signal over a time long compared with the fundamental period, a much slower variation in signal strength is found to be present. This signal represents the reradiation from the main airframe and scattering centers located about the aircraft. Figure 16 shows the echo intensity from an AT-11 aircraft, head-on, averaged over intervals of 0.03 sec and plotted for 3.2 sec. These measurements were made from pulse-to-pulse A-scope photographs and show a fading exceeding 10 db. A frequency analysis of the data indicates a maximum in the spectrum of about 0.6 cps.

This flucturation, slow compared with propeller modulation, is almost entirely attributable to the fine lobe structure of the radar cross section as a function of aspect. One would expect the width of the lobes to be given roughly by $\lambda/2\ell$, where ℓ is some characteristic length of the airplane. Thus at 10 cm, with $\ell = 30$ ft, the width of the lobes should be of the order of magnitude of 0.3°. An airplane in flight will change aspect by many times this figure, yawing being the most important motion for these considerations. These small changes in aspect due to yaw give rise, therefore, to large changes in the echo. Figure 17 shows a record taken by Ashby and Martin of the signal strength from a B-26 bomber as a function of azimuth (Ref. 14).

Because of the extended nature of propellers, the backscatter cross sections of propeller-driven aircraft have large doppler signatures extending over $\pm 70^\circ$ around the fore/aft axis of the aircraft. Figure 17 indicates the wide angular detection range of a B-26 aircraft.

Fan engines on the other hand, because of the presence of the fan, should have a much more restricted angular visibility which should confine the Doppler signature of the fan blades to $\pm 10^\circ$.

Moving-Target Indication (MTI) Radar

The doppler shift in frequency caused by a moving target may be used in pulse radar to distinguish moving targets from clutter. Doppler permits the pulse radar to discern moving targers in the presence of fixed targets and clutter even when the echo signal from fixed targets is orders of magnitude greater. The ordinary pulse radar which does not use doppler information does not have this capability. The fixed-target echoes with which the desired target echo must compete are those included within the same radar resolution cell as the target, or those which enter the radar receiver via the antenna sidelobes. (The radar resolution cell in this instance is the volume illuminated by a pulse packet.) Echo signals from fixed targets and clutter are not shifted in frequency, but the echo from a target moving with relative velocity v_r will be shifted in frequency by an amount given by the doppler formula $f_d = 2v_r/\lambda$, where λ is the wavelength of the transmitted signal. The fixed targets are called clutter, an especially appropriate name since they tend to "clutter" the cathode-ray tube display with unwanted information.

Early pulse radars did not make use of the doppler information inherent in the echo signal from moving targets. Consequently, they were sometimes of little value in regions where large clutter echoes existed. But by the end of World War II the techniques and components for extracting doppler information with pulse radar were developed. In the postwar years they were improved upon, and most modern search radars usually include some means of extracting the doppler information to detect moving targets in the presence of clutter. A pulse radar which makes use of the doppler information is known as an MTI radar, which stands for moving-target indication. In practice a distincition is sometimes made between the MTI radar and the pulse-doppler radar, although they are both based on the same physical principle. MTI usually refers to a radar in which the doppler-frequency measurement is ambiguous but the range measurement is unambiguous. In the pulse-doppler radar the doppler measurement is usually unambiguous and the range may or may not be ambiguous. Ambiguous range means that multiple-time-around echoes are possible, while ambiguous doppler implies that "blind speeds" fall within the expected target speeds.

Typically, MTI radar can extract the moving-target echo from the clutter echo even if the clutter echo is 20 to 30 db greater than the moving-target echo. Some pulse-doppler radars can detect moving targets in closing situations with a stationary background when the clutter echo is 70 db greater than the target echo.

Reflectivity of Propeller Blades

Because of the complex shape and construction of propeller blades, the radar reflectivity of a blade is measured by means of backscatter tests. To evaluate the importance of some of the structural aspects of propeller blades, 38 backscatter tests were conducted at Electronic Space Structures on their 575 ft range using 9.5 GHz, 100 nanosecond pulse radar (Ref. 16). Structurally equivalent monocoque and cover-spar blades were tested at all azimuth and blade angle positions. Only the outer two-thirds of the blades were exposed in order to obtain a true comparison of the differences in construction. Also, the effects of the leading edge erosion strip and the semiconductive paint were evaluated, and a plain spar and equivalent all-metal blade were tested. The maximum radar cross section for both the monocoque and cover-spar blades tested was about 14.5 m^2 and occurred at about 0^o and 180^o, when the face and camber sides of the blade were normal to the radar beam. However, for leading and trailing edge incidence the monocoque blade had a radar back scatter about 8 db lower than the cover-spar blade, but in this mode the radar cross section of the monocoque blade was only about 0.1 m^2. The polarization of the radar had little effect on the reflectivity from the face and camber sides, whereas it made a significant difference for the edge-wise incidence.

Although at normal incidence the face and camber sides of a fiberglass-shell, steel-spar blade presents radar cross sections only about a third of those for an all-metal blade, their radar cross sections are still quite large. The projected face or camber side cross-sectional area of the test blades was about 0.570 m^2, which resulted in a radar cross section of about 14.5 m^2 for an all-fiberglass or a fiberglass-covered, steel-spar blade, and 46 m^2 for an all-metal blade.

For a 3-way propeller the radar incidence is normal to only one blade at a time. For a 4-way propeller, two blades could be exposed to normal incidence at a time, so that for the same propeller solidity, the radar cross section could be about $1\frac{1}{2}$ times as great.

Reducing the Reflectivity of Propeller Blades

There are basically two methods for reducing the radar cross section of the propeller blade - by modifying the construction and by using special radar-absorptive or transparent materials. The improvement that can be obtained with the former is somewhat limited because of the difficult structural requirements the blade must meet. Parametric analysis of the blade structure shows that the optimum blade design consists of a very thin fiberglass shell and steel spar with a width 28% to 43% of the blade chord. Such requirements are consistent with those for minimum radar reflectivity which decreases with shell thickness and core width. Thus, the spar width of the shell-spar blade should be decreased from its present 50% to 33%. The shell thickness of the cover spar blade should be decreased from its present 0.027 in. to 0.081 in. to thicknesses of 0.018 in. to 0.054 in., and a nonmetallic erosion strip should be used. Such geometry changes should result in reducing the radar backscatter about 2 db. Shaping of the edges of the spar and matching of cover and foam thickness do not appear worthwhile or feasible from a manufacturing stnadpont. Obvious from these estimated results is that special radar material must be used to drop the radar cross section a significant amount.

Four possible blade constructions for reduced radar backscatter are depicted in Fig. 18. Table III gives the estimated reduction in radar reflectivity for X, C, and S bands. Construction No. 1 would involve a thin shell with loaded, absorbing foam and wrapping the spar with a 0.10 in. thick, solid, multimatched, loaded dielectric material (Schmitt absorber). Possibly the shell material could be graded to improve its transparency. The reflectivity of the free shell should decrease towards the S band, whereas the reverse in true for the wrapped core. About an 8 to 10 db reduction in backscatter would probably be realized for such a construction. This design poses no manufacturing, structural, weight, or performance problems because it uses the present shell material, and the slight increase in blade thickness caused by the wrapping on the spar would have an insignificant effect on performance. If necessary a magnetic film skin effect absorber (Hansen) would be used on the leading and trailing edges of the spar.

Construction No. 2 would be the same as No. 1, but the shell thickness and loading would be made to match the loaded fill. Such a construction would probably result in about 8 to 14 db reduction in radar backscatter. The special shell material of this construction might introduce structural and manufacturing problems, but otherwise it would be the same as the first design.

For the third and fourth designs the entire shell is made of the solid, multimatched, absorbing material. Because the absorbing materials are about 0.100 in. and 0.180 in. thick, respectively, the blade will be slightly thicker and heavier. The optimum blade from a weight standpoint is one with a thin shell. The potential problems are the structural and erosion capabilities of the absorbing materials. It is estimated that these constructions will result in about 8 to 16 db and 10 to 18 db reductions, respectively, for the No. 3 and No. 4 constructions. In both cases the lower estimated radar cross section is for X band and the larger is for S band. To decrease the radar cross section for the S band still further, a thicker absorbing shell must be used, which will add additional weight and degrade the aerodynamic performance.

Table III indicates the expected reduction in RCS using the most optimistic camouflaging techniques.

Powerplant Detection Range Comparison

Summarized in Fig. 19 is the relative effect of aircraft engines on the detectability of the aircraft by conventional and MTI radar systems. Using the basic airframe to determine the minimum detection range, the relative increase in aircraft detectability with different engines is evaluated. It can be seen that the availability of a Doppler signature and the ability to suppress clutter permits the detection of a turboprop aircraft at a far longer range than a turbofan aircraft. Of all considerations, this appears to be the most significant, particularly as MTI improvements are rapidly producing radar with 40 db sub-clutter visibility.

DISCUSSION OF RESULTS

In summary, the data obtained in this brief study confirm the belief that noise control and radar detection considerations are important in the design of a powerplant for the airborne tactical control mission. Control of the cabin vibration caused by propeller blade passing is also significant.

The data generally support a conclusion that a turbofan would offer a significant improvement in noise, vibration, and radar characteristics over the current T56 turboprop installation. However, it must not be inferred that the T56 represents an optimum turboprop for the airborne tactical control mission. Propeller tip speed and blade diameter can be reduced by using more efficient blade design and/or using more blades (up to 7 blades might be considered). Special propeller construction for reducing radar reflectivity has been discussed.

Even so, the magnitude of the problems presented by the turboprop, when viewed in the context of an aircraft design that is severely limited by the constraints imposed by carrier handling, warrants consideration of a radical departure from conventional turboprop design. Because the aircraft speed requirements for the airborne tactical control mission are low (200-250 kts), a shrouded propeller may offer an attractive solution in terms of an optimum turboprop design. It is therefore considered appropriate to emphasize a careful determination of performance tradeoffs among turbofan, turboprop, and shrouded turboprop installations during the remainder of the study covered by this contract. After these performance tradeoffs are determined, further detailed study of the noise, vibration, and radar characteristics will probably be warranted, very possibly including "ad hoc" experimental programs. In any case, any Proposed Technical Approach for a future airborne tactical control propulsion system should certainly make provision for extensive work in the area of noise, vibration, and radar characteristics.

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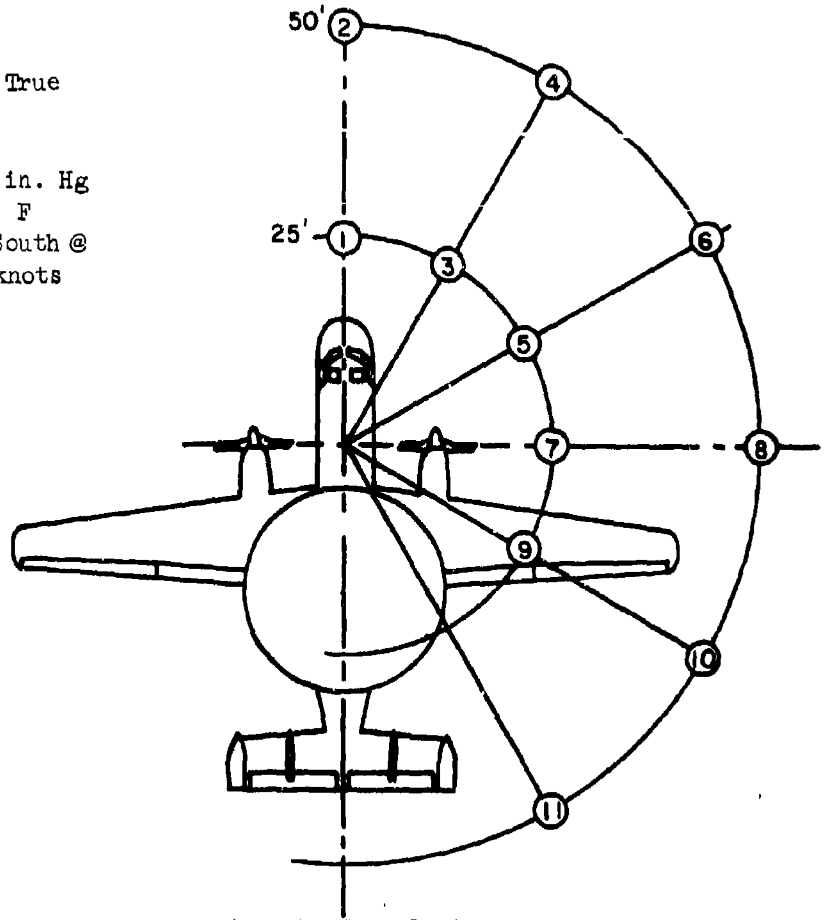
TABLE I

MEASURED EXTERNAL E-2A ACOUSTICAL NOISE LEVEL

GROUND OPERATION - MILITARY POWER

110° True

29.83 in. Hg
46° F
Wind South @
6 knots



Octave Band Analysis

(Sound Pressure Levels in db Referred to 0.0002 dynes/cm²)

cps

Position No.	Position		Overall	35.5-75	75-150	150-300	300-600	600-1200	1200-2400	2400-4800	4800-10Kc
1	0°	25ft	125	112	117	120	118	117	111	106	98
2	0°	50ft	121	114	113	117	112	112	107	103	94
3	30°	25ft	126	120	118	121	119	116	110	105	96
4	30°	50ft	124	120	117	117	112	112	107	102	93
5	60°	25ft	130	128	122	120	121	117	111	107	99
6	60°	50ft	126	123	119	117	113	114	108	102	95
7	90°	25ft	132	128	126	126	117	117	111	106	98
8	90°	50ft	132	130	125	117	112	110	108	102	95
9	120°	25ft	133	130	127	124	114	113	109	106	98
10	120°	50ft	130	130	115	116	110	109	105	101	91
11	150°	50ft	124	121	117	118	114	111	105	100	93

TABLE II

E-2A COCKPIT AND CABIN VIBRATION SURVEY-SUMMARY OF TEST RESULTS

Indicated Airspeed Knots	Indicated Altitude Feet	Condition	Pilot's Seat: Seat Level Vertical Dir. Double Ampl. Inches *	Pilot's Seat: Chest Level Long. Dir. Double Ampl. Inches	ACO Seat Chest Level Lat. Dir. Double Amp. Inches	Pilot's Control Column Long. Dir. Double Ampl. Inches	ACO Work Table: Lat. Dir. Double Ampl. Inches	ACO Work Table: Long. Dir. Double Ampl. Inches
80	--	Take-off Ground Roll	(0.0106-12cps) 0.0140	(0.0024-25cps) 0.0042	(0.016-18cps) 0.0184	(0.030-12cps) 0.0365	(0.010-12cps) 0.0138	(0.004-12cps) 0.0057
120	400	Take-off Climb Out	(0.0046-72cps) 0.0070	(0.0034-72cps) 0.0047	(0.006-12cps) (0.004-18cps) 0.0071	(0.012-72cps) 0.0142	0.0011	0.0015
275	7500	Level Flight Military Power	(0.0036-18cps) 0.0048	0.0035	0.0054	(0.010-72cps) 0.0128	0.0028	0.0015
117	30000	Low Speed Cruise	0.0028	0.0019	0.0019	(0.0036-72cps) 0.0040	0.0019	0.0010
164	30000	High Speed Cruise	0.0039	0.0035	0.0030	(0.0050-72cps) 0.0061	0.0022	0.0018
146	30000	Loiter	0.0028	0.0017	0.0028	(0.0040-72cps) 0.0049	0.0022	0.0010

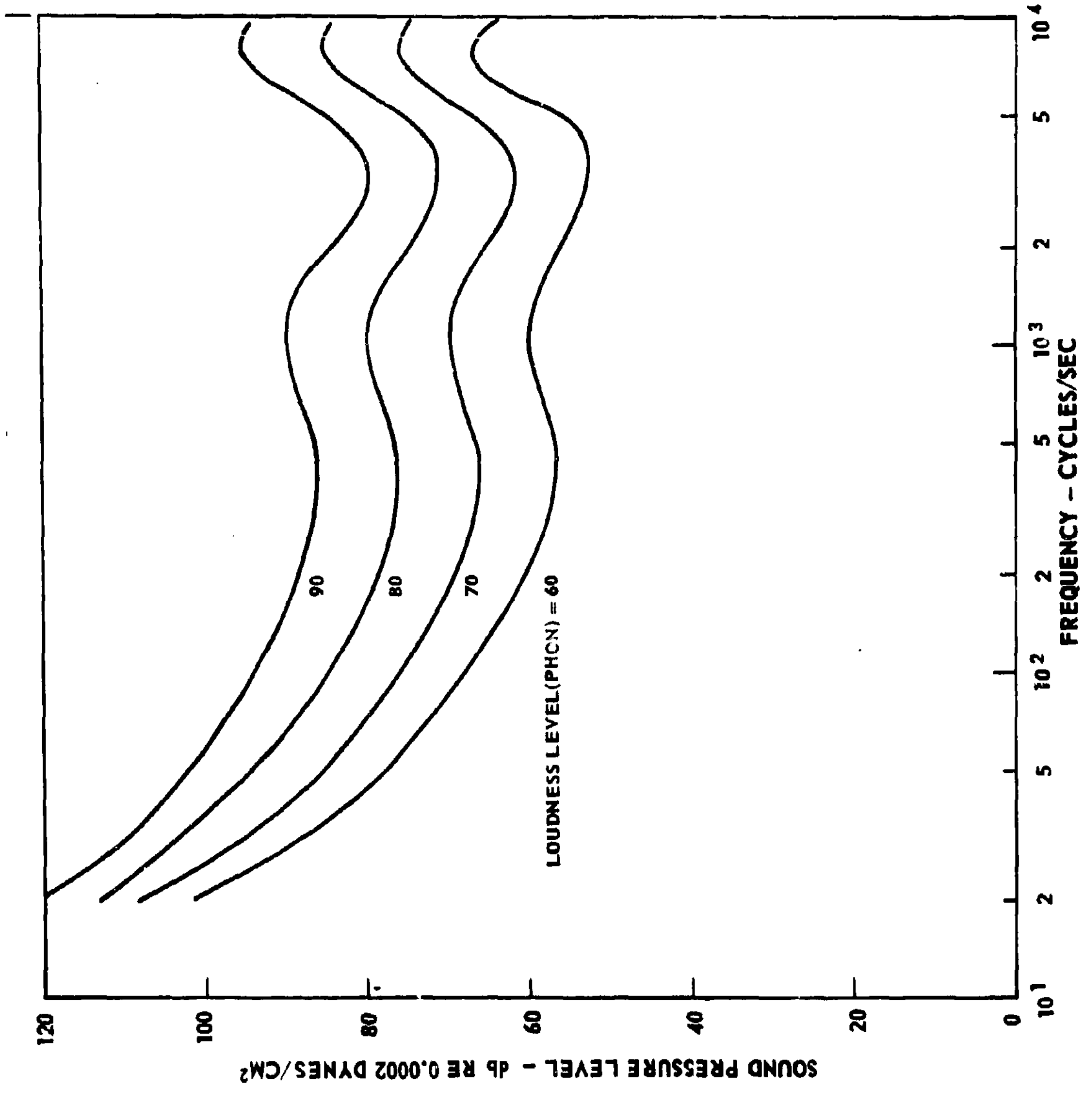
* Data tabulated are displacement of complex wave. Data in parenthesis are major discrete frequencies of complex wave.

TABLE III

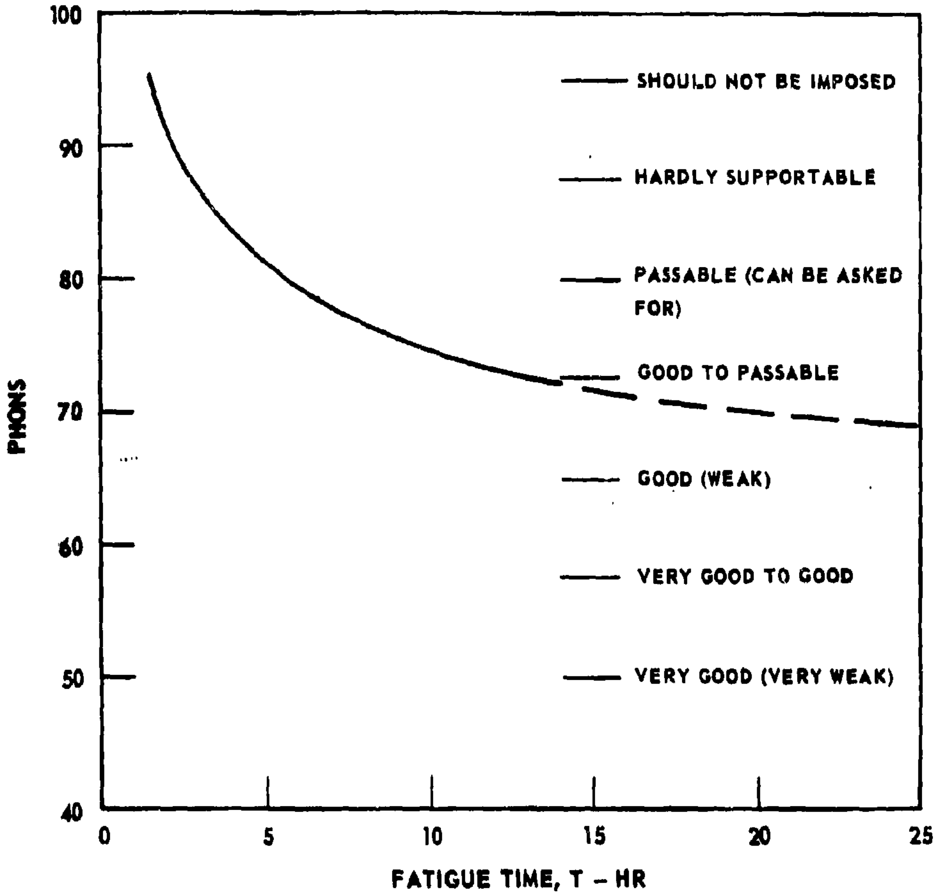
ESTIMATED REFLECTIVITY IMPROVEMENTS FOR POSSIBLE PROPELLER BLADE DESIGNS

Blade No.	Construction and Materials	Aspect	Radar Cross Section Reduction - DB Down					
			S Band		C Band		X Band	
			Inboard	Tip	Inboard	Tip	Inboard	Tip
1	1. Spar Wrapped with Multimatch Abs.	Trailing Edge	8	10	10	12	3	10
	2. Fill Loaded	Face & Camber	8	8	10	10	8	8
	3. Shell Unmatched	Leading Edge	8	8	10	10	8	10
2	1. Same as #1, but Shell Matched to Fill	Trailing Edge	8	12	12	14	12	14
		Face & Camber	8	8	10	10	10	10
		Leading Edge	8	10	10	12	10	12
3	1. Shell Complete 0.10" Multimatch Absorber	Trailing Edge	6	8	10	12	14	16
		Face & Camber	8	8	10	10	12	12
		Leading Edge	6	6	10	10	12	12
4	1. Shell Complete 0.18" Multimatch Absorber	Trailing Edge	10	12	12	14	16	18
		Face & Camber	10	10	12	12	14	14
		Leading Edge	10	10	12	12	14	14

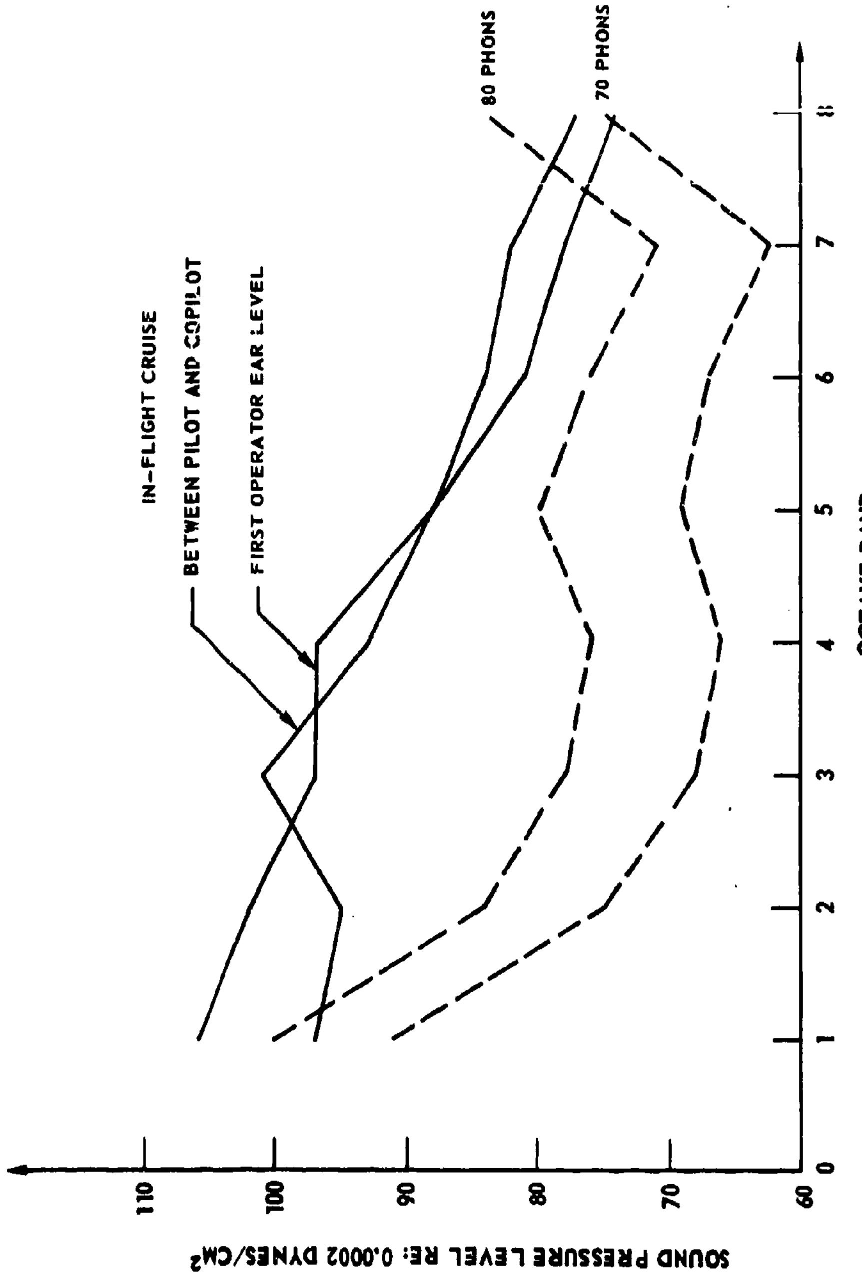
EQUAL LOUDNESS LEVELS



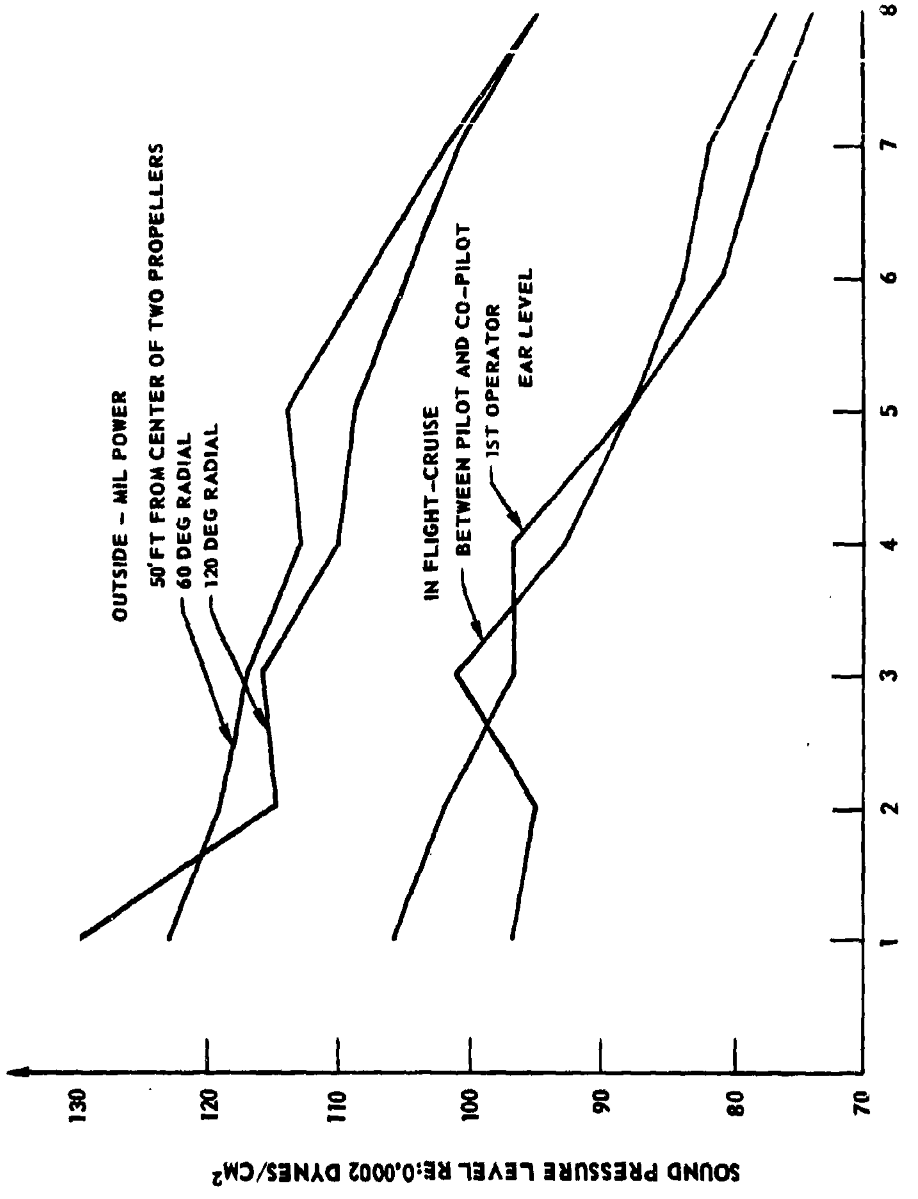
NOISE TOLERANCE

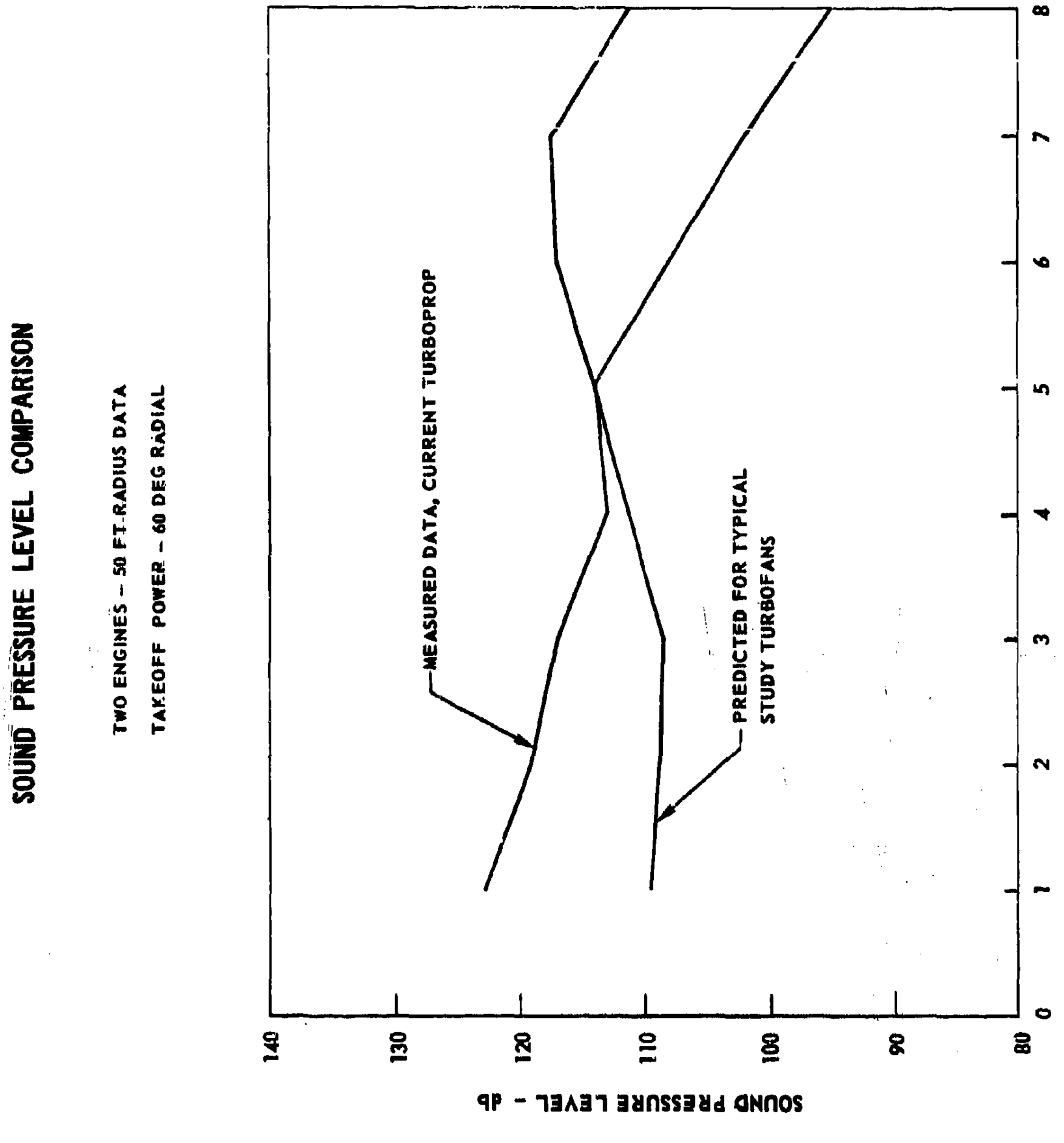


CURRENT E-2A NOISE PROBLEM



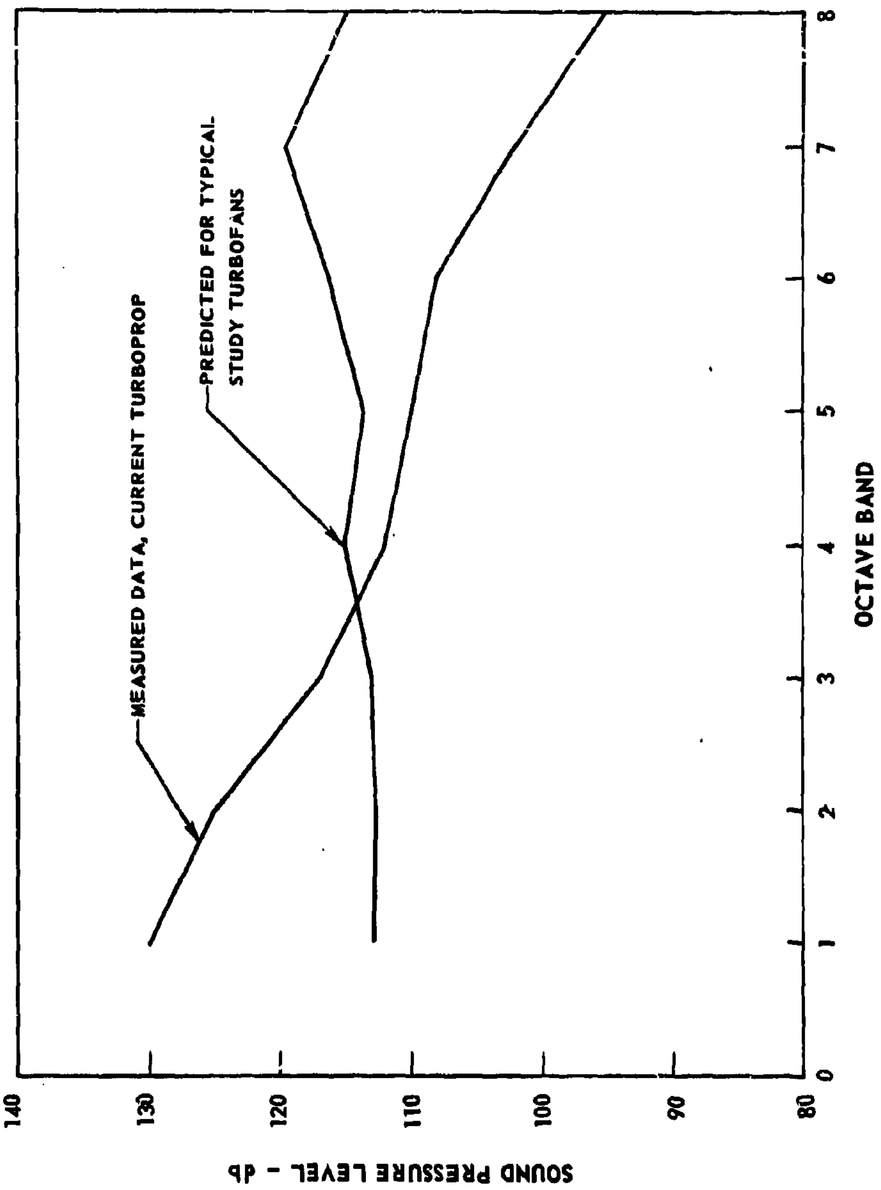
COMPARISON OF ACOUSTICAL NOISE MEASUREMENTS — CURRENT E-2A




SOUND PRESSURE LEVEL COMPARISON
TWO ENGINES - 50 FT-RADIUS DATA
TAKEOFF POWER - 60 DEG RADIAL
MEASURED DATA, CURRENT TURBOPROP
PREDICTED FOR TYPICAL STUDY TURBOFANS
SOUND PRESSURE LEVEL - dB
140
130
120
110
100
90
80
0
1
2
3
4
5
6
7
8
OCTAVE BAND

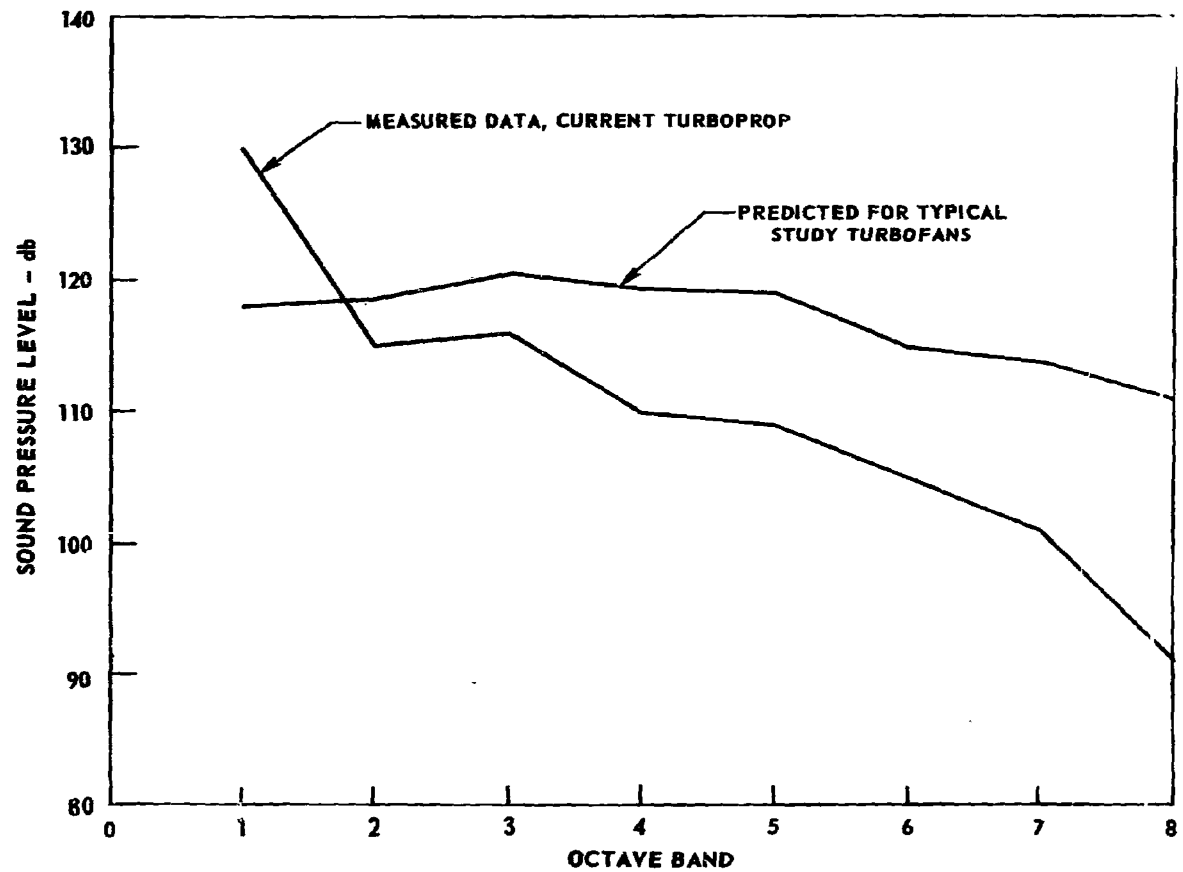
SOUND PRESSURE LEVEL COMPARISON

TWO ENGINES – 50 FT RADIUS DATA
TAKEOFF POWER –90 DEG RADIAL

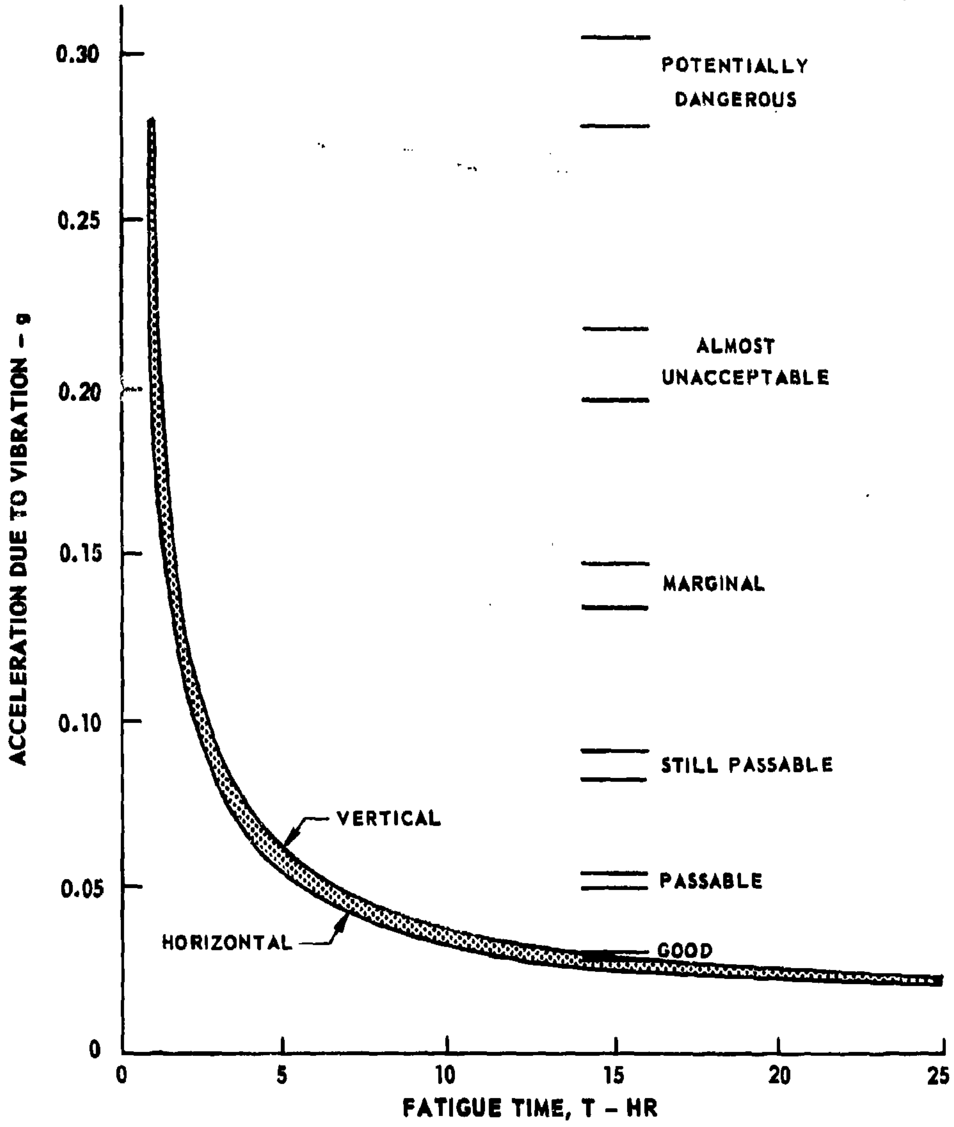


SOUND PRESSURE LEVEL COMPARISON

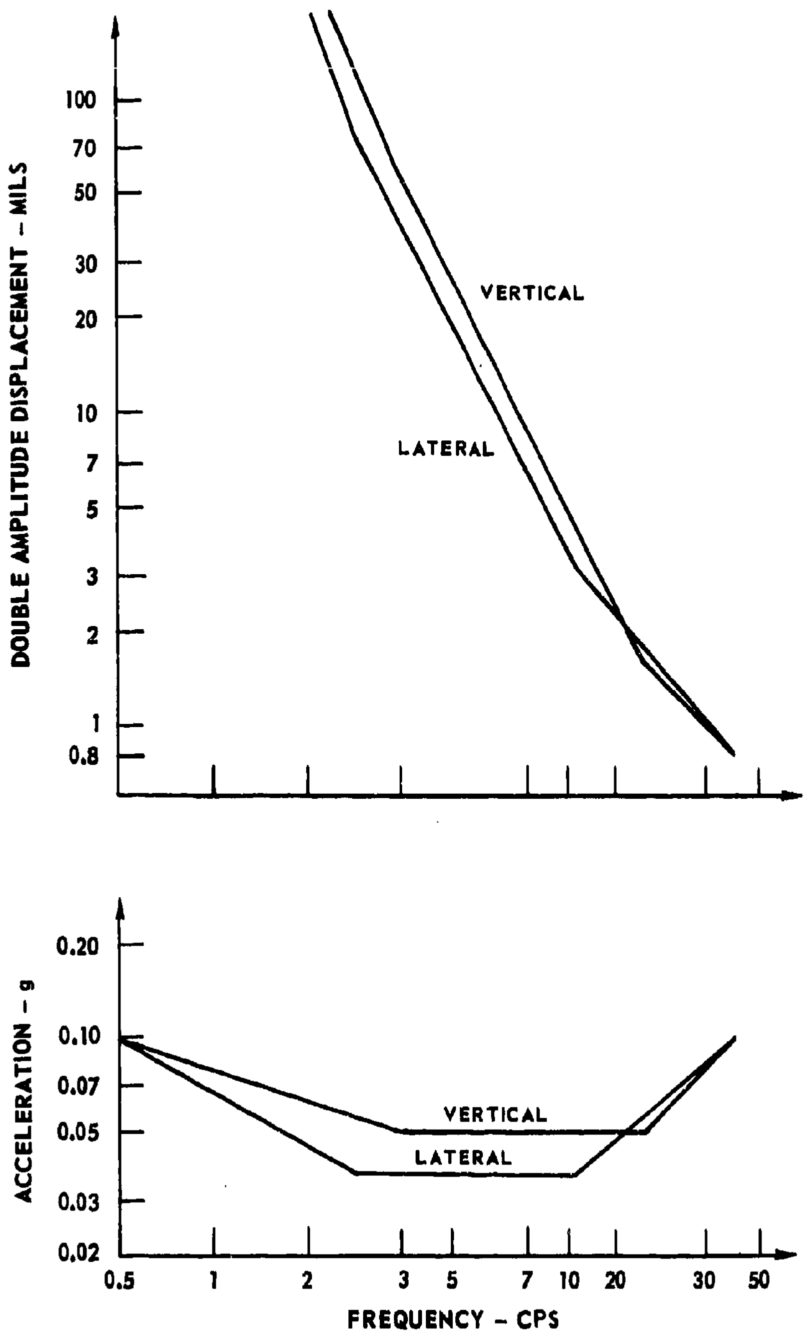
TWO ENGINES – 50 FT RADIUS DATA
TAKEOFF POWER – 120 DEG RADIAL



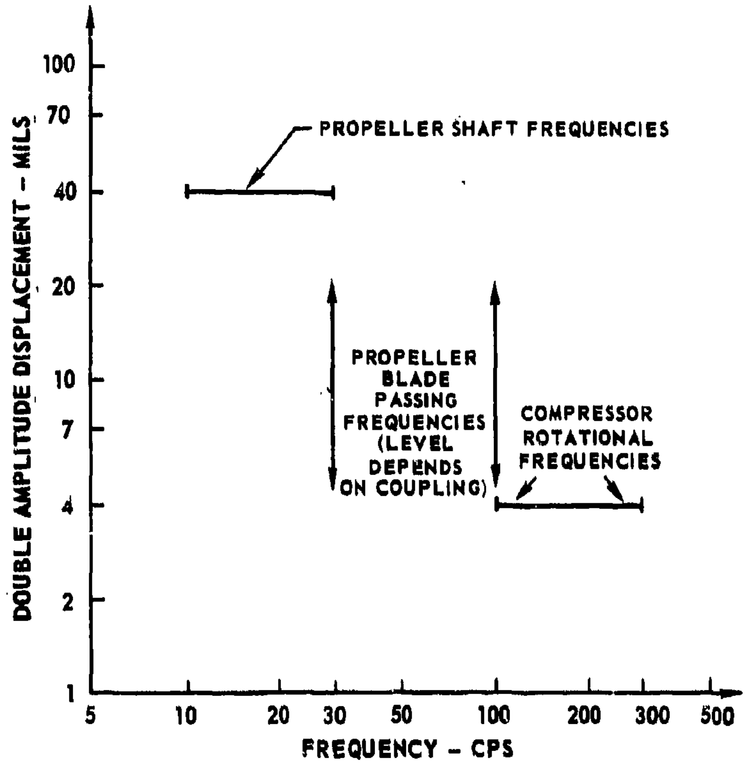
VIBRATION TOLERANCE



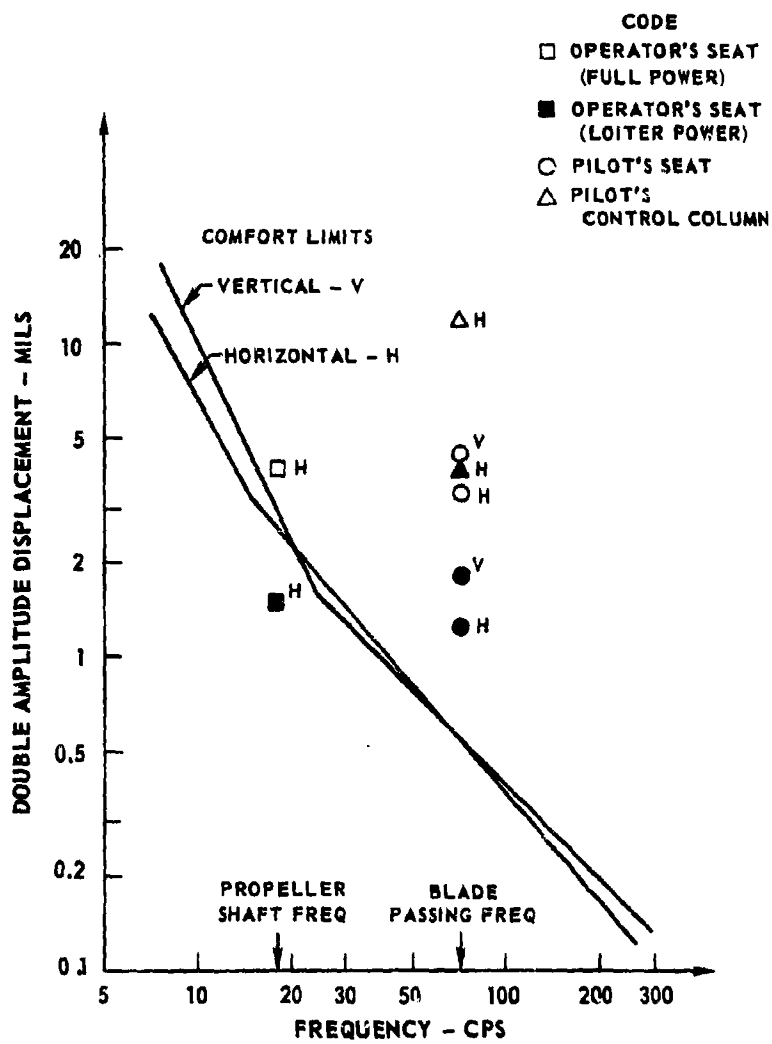
RECOMMENDED VIBRATION COMFORT LIMITS



PROPULSION SYSTEM VIBRATION SOURCES

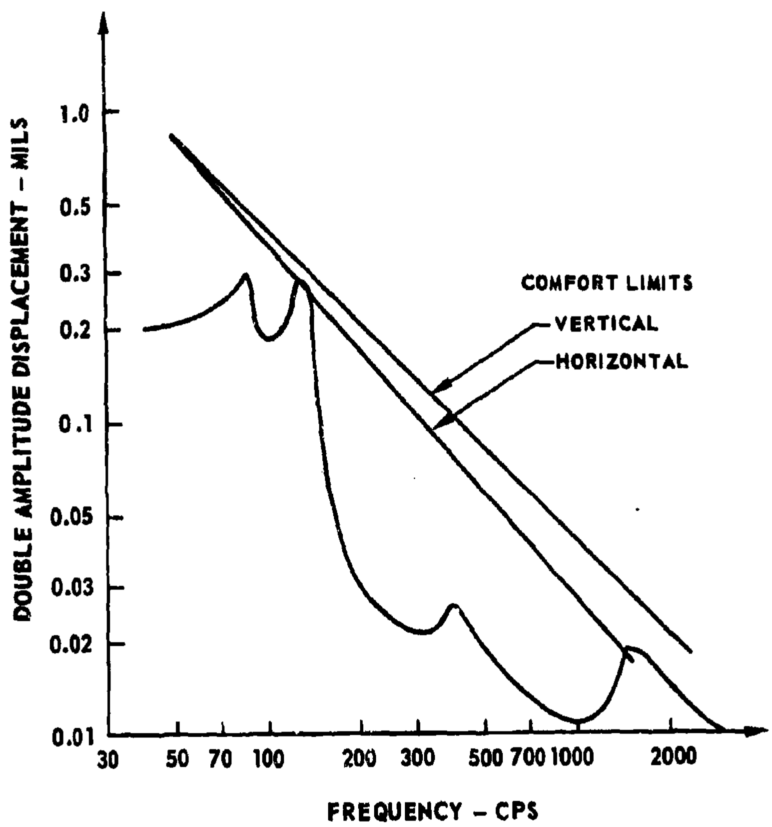


CURRENT E-2A VIBRATION PROBLEM

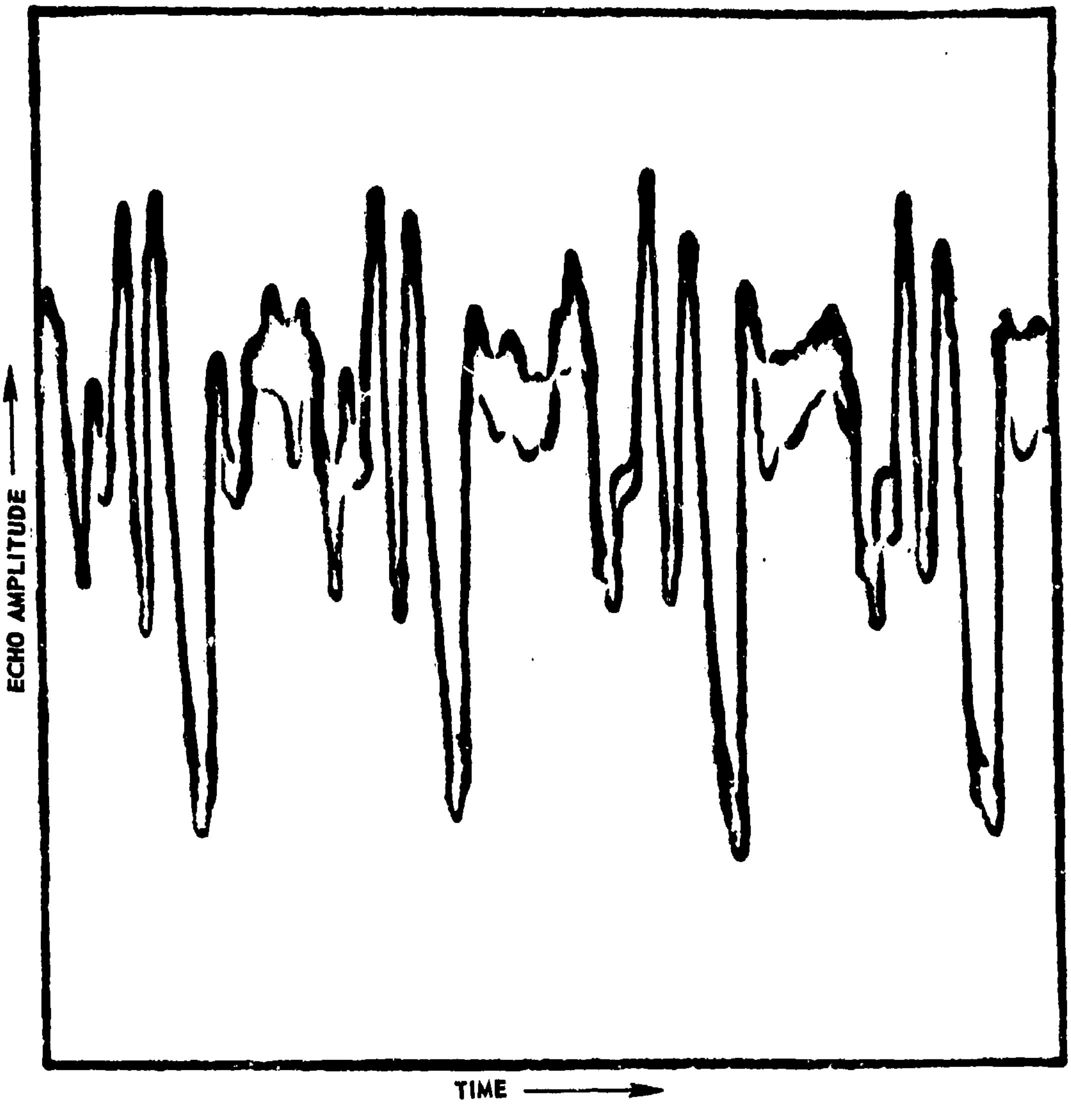


SPECTRAL DISTRIBUTION OF VIBRATION MEASURED ADJACENT TO FT4 FRONT MOUNT (ENGINE SIDE)

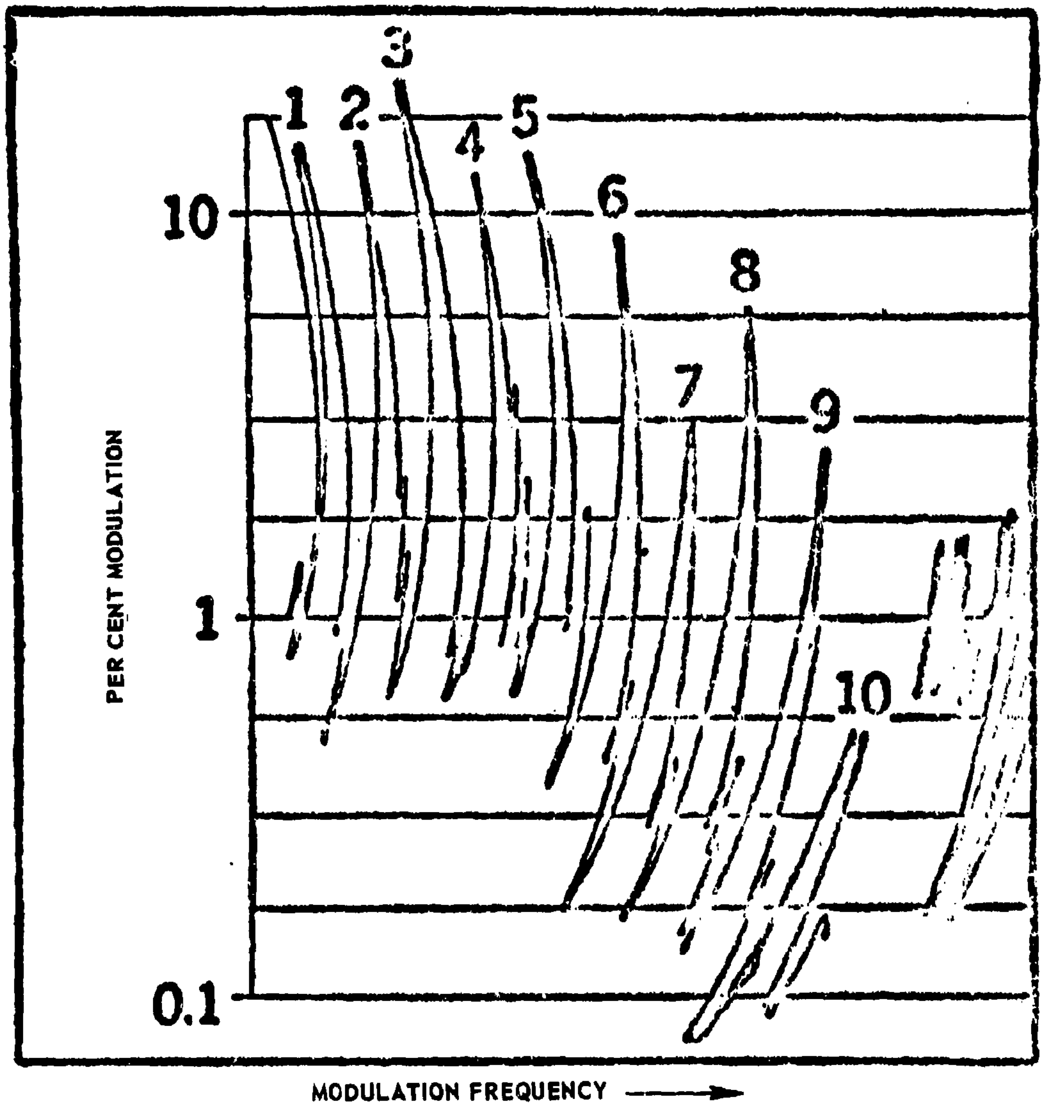
(ENGINE OPERATION AT 60% POWER)



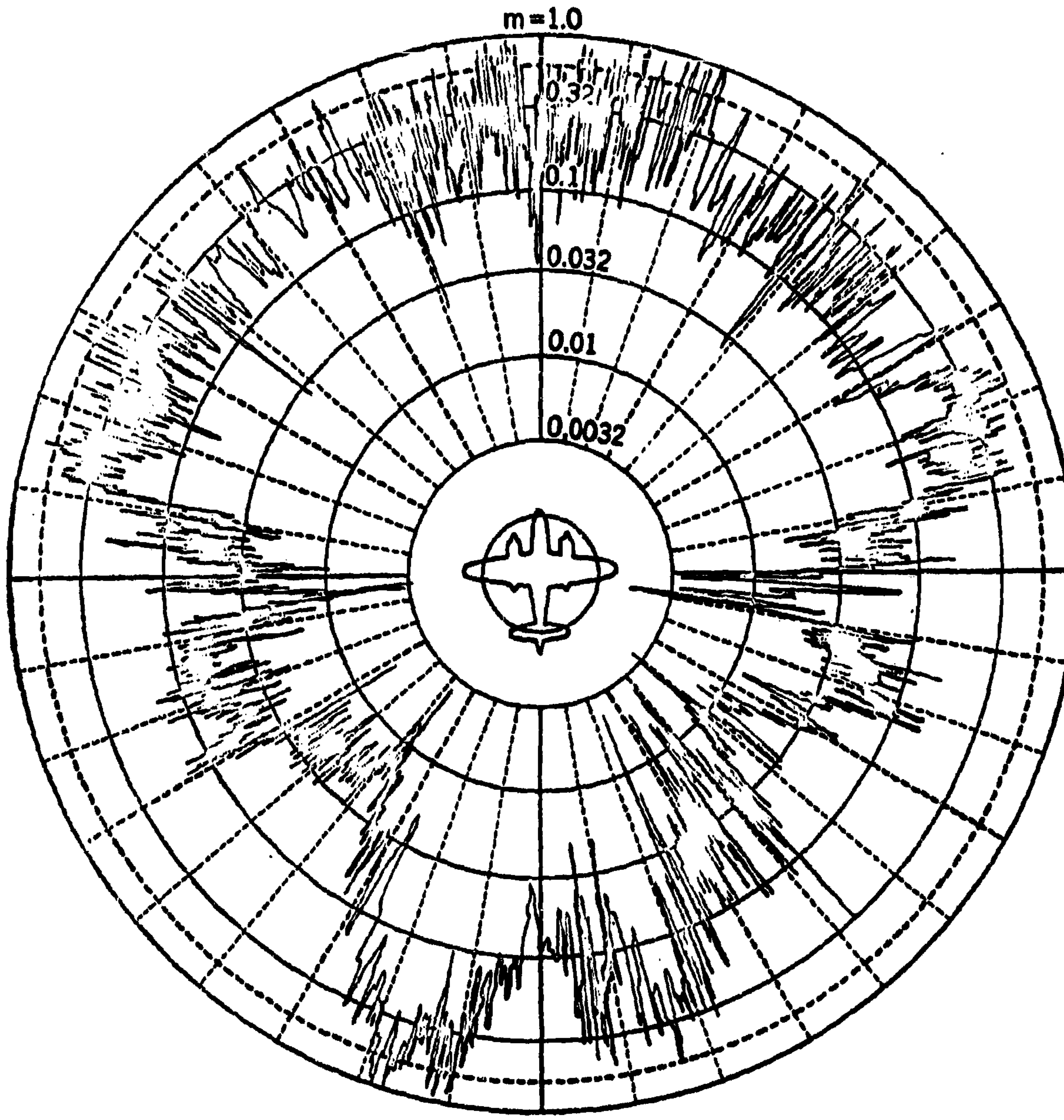
MODULATION FROM PROPELLER ROTATION ON THE 10-CM ECHO FROM A B-26



FREQUENCY SPECTRUM OF THE MODULATION SHOWN IN FIG. 15

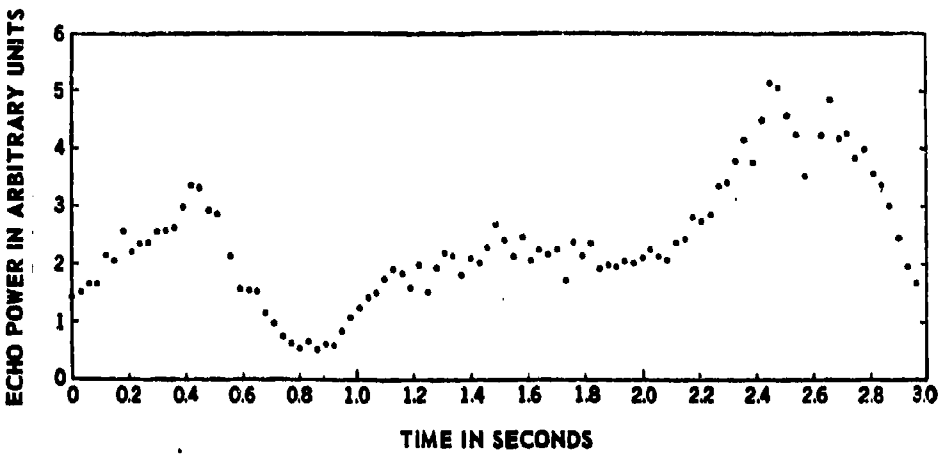


PROPELLER MODULATION OF THE ECHO ON 10-CM FROM A B-26 BOMBER

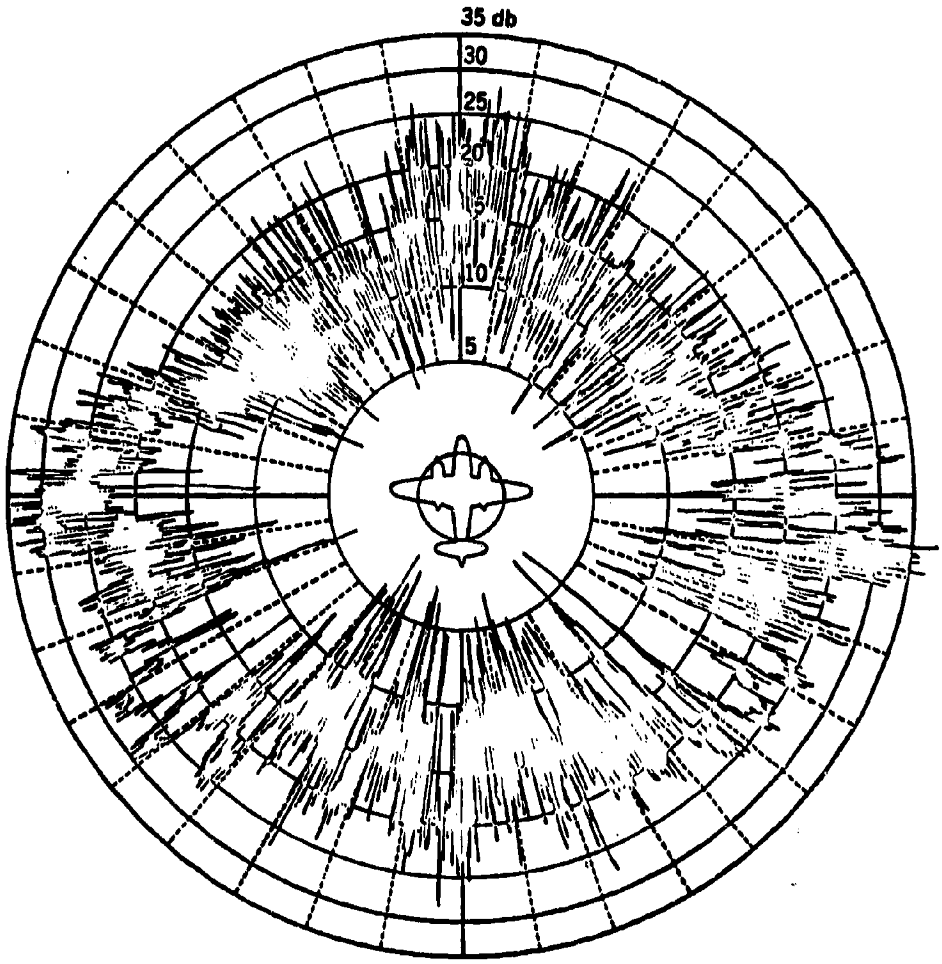


THE ECHO FROM AN AT-11 AIRPLANE ON 9-CM AS A FUNCTION OF TIME

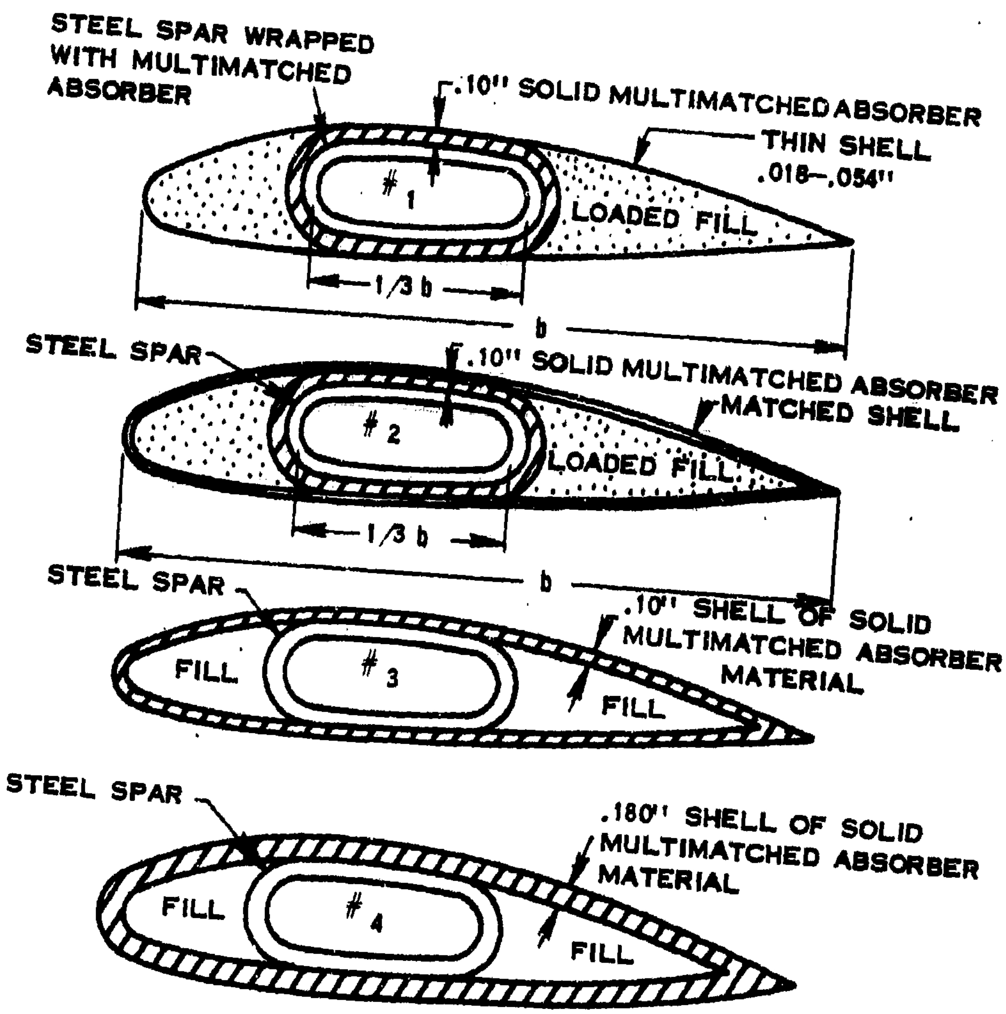
EACH POINT REPRESENTS AN AVERAGE OVER A 30-msec PERIOD



ECHO ON 10-CM FROM A B-26 BOMBER AS FUNCTION OF AZIMUTH



POSSIBLE PROPELLER BLADE CONSTRUCTION FOR LOW RADAR REFLECTIVITY



EFFECT OF PROPULSION ON RADAR DETECTION